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13. ABSTRACT *(Maximum 200 words)*

During the past ten years, DOD sponsors over 35 research programs, which Dr. Chen served or has been serving as a principal investigator. All of them are focused on one area - "Optical Interconnects" which is directly related to "Optical Materials (4)", "Polymeric Materials (11)" and "Optoelectronic Computer Networking (13)" of the BMDO/DURIP solicitation. The major thrusts for the existing BMDO program are to generate polymer-based true time delay (TTD) module and to build a system demonstration for phased array antenna using BMDO-sponsored polymer-based active and passive photonic devices. High-speed polymer-based EO modulator arrays and polymer-based optical true-time delay modules have been built through the existing programs involving UT Austin (Chen), USC (Steier), UCLA (Fetterman) and Univ. of Washington (Dalton). These devices will be implemented onto a real phased array antenna system driving by polymer-based optoelectronic components. At the UT Microelectronics Research Center we maintain all almost needed fabrication facilities to realize the proposed devices. The equipment required to fulfill the committed task constitutes a "Laser Enhanced End Point Detection Plasma Etching System" through which the fine features of the devices can be fabricated. In 2000, we received financial support from DOD's funding agency, MDA, to acquire a Plasmalab 80 Plus laser enhanced end point detection etch tool from Oxford Instrument Corporation to serve the purposes described above. This system exhibits full laser enhanced end point detection with the accuracy better than + 0.1 um. Several DOD optical interconnects project have been benefited through the use of this laser, which has been use to fabricate various optoelectronic devices.

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Final Report
Contract No. F49620-01-1-0362

Laser Enhanced System for Ultra-Fine Microstructure Formation

Submitted to

Dr. Charles Lee
AFOSR

Submitted by
Ray Chen
Microelectronics Research Center
University of Texas, Austin

11/30/2002

1. The Grant and Its Purpose

During the past ten years, DOD sponsors over 35 research programs, which Dr. Chen served or has been serving as a principal investigator. All of them are focused on one area—"Optical Interconnects" which is directly related to "Optical Materials (4)", "Polymeric Materials (11)" and "Optoelectronic Computer Networking (13)" of the BMDO/DURIP solicitation. The major thrusts for the existing BMDO program are to generate polymer-based true time delay (TTD) module and to build a system demonstration for phased array antenna using BMDO-sponsored polymer-based active and passive photonic devices. High-speed polymer-based EO modulator arrays and polymer-based optical true-time delay modules have been built through the existing programs involving UT Austin (Chen), USC (Steier), UCLA (Fetterman) and Univ. of Washington (Dalton). These devices will be implemented onto a real phased array antenna system driving by polymer-based optoelectronic components. At the UT Microelectronics Research Center we maintain all almost needed fabrication facilities to realize the proposed devices. The equipment required to fulfill the committed task constitutes a 'Laser Enhanced End Point Detection Plasma Etching System' through which the fine features of the devices can be fabricated. In 2000, we received financial support from DOD's funding agency, MDA, to acquire a Plasmalab 80 Plus laser enhanced end point detection etch tool from Oxford Instrument Corporation to serve the purposes described above. This system exhibits full laser enhanced end point detection with the accuracy better than ± 0.1 μm. Several DOD optical interconnects projects have been benefited through the use of this laser- enhanced etching system, which has been used to fabricate various optoelectronic devices and systems for field demonstration.

2. Description of the Equipment

Figures 1 and 2 respectively show a diagram of the features of Plasmalab 80 Plus laser enhanced end point detection etch tool from Oxford Instrument.

The system consists of

- Laser interferometer end point detection system integrated with the system control software. Comes complete with motorized x,y table, closed circuit TV camera and pop up control and data display windows.
- PC2000 system control hardware and software for the Plasmalab 80 Plus. This software is integrated with the laser endpoint detection system and displays a TV image of the laser spot as it is lined up on the wafer surface. A graphical image of the etch and end stop is also displayed.
- Universal base console housing the electronic sub systems, control units, and pneumatics.
- RIE process chamber with single viewport. Includes a glovebox (standard height)

- 240mm water cooled lower electrode with helium assisted heat transfer. Comes complete with wafer clamping. Heater chiller unit is included.

- 60/600 watt RF generator and automatic matching unit connected to the lower electrode.
- Vacuum measurement is achieved with a 1 Torr capacitance manometer and active penning gauge
- Two external six line gas pods. The tool is fitted with a total EIGHT mass flow controlled gas lines. This means that gas pod #1 will be FULL (six mass flow controlled gas lines), whilst the other will have TWO mass flow controlled gas lines fitted (leaving four empty slots for future mass flow controlled gas lines to be added). The Mass flow controlled gas lines that are to be provided with this tool are, N_2 (non toxic), O_2 (non toxic), SF_6 (non toxic), BCL_3 (toxic), $SiCl_4$ (toxic), H_2 (toxic), Ar (non toxic), CF_4 (non toxic).
- 63 mm pumping port with separate isolation valve and automatic pressure controller.
- 400l/s turbo pump backed by a $33m^3hr$ Fomblin rotary pump with filters for use with the process chamber.

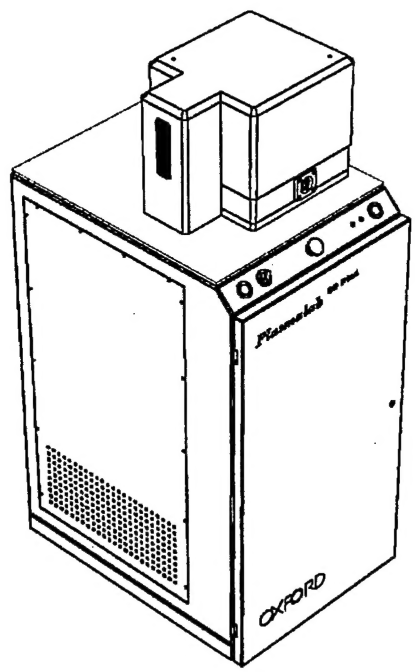


Figure 1. The Drawing(photo) of Laser Enhanced End Detection Etching System

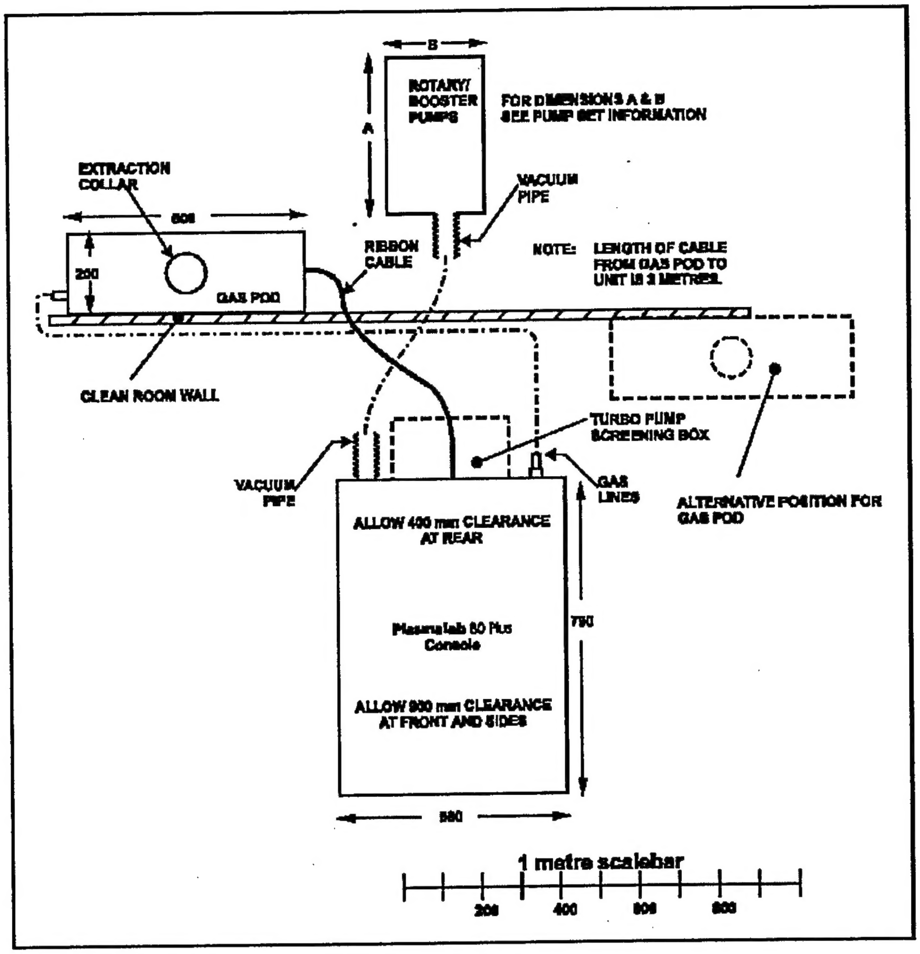


Figure 2. The system footprint

Laser Enhanced End Point Detection Feature

The laser enhanced end point detection for the systems combines the SOFIE optical hardware with the powerful PC2000 system control software to provide a fully integrated end point detection system. The system provides the capability of end point detection, etch rate determination and etch-to-depth control.

Hardware

The SOFIE LD205 laser interferometer consists of:

- Single beam solid state diode with stabilized output power and single wavelength at 670nm.
- Integral CCD camera for combined laser spot and substrate pattern imaging.
- Manual X-Y table for laser spot positioning (motorized table available).
- PMT sensor.

The hardware package is mounted directly on top of the plasma chamber with a vertical line of sight to the centre of the substrate electrode

Software

The control software is an integral part of the Plasmalab system software, PC2000. The system is simple to use, includes a pull down window for displaying the CCD image, and has control features such as

- Normalisation - for scaling the signal
- Closed time - to avoid false endpoints
- Active - to alert for impending end point
- Confirmation - to establish end point validity
- Endpoint - to establish an endpoint marker
- Overetch - for completing the etch process

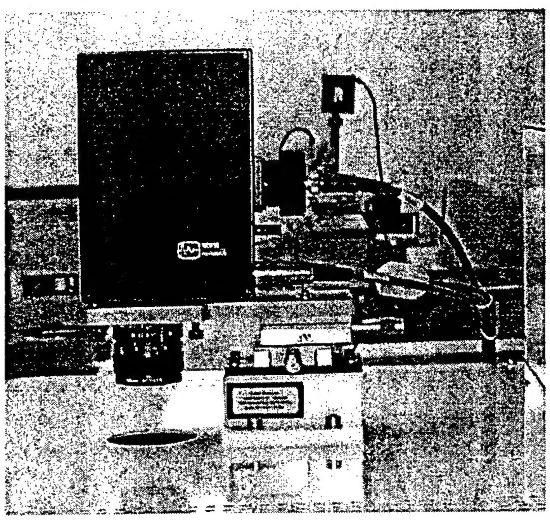


Figure 3. The Photo of Laser Enhanced End Point Detection Feature

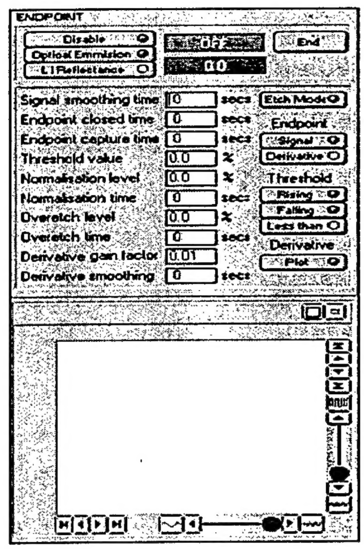
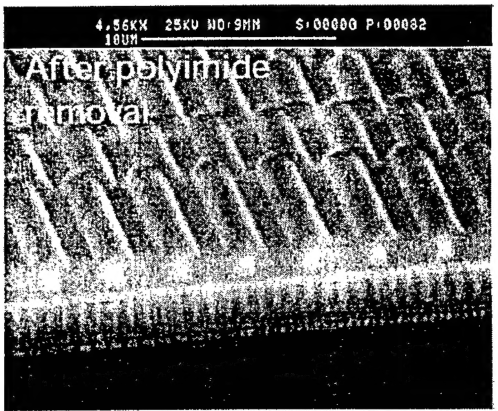


Figure 4. PC2000 Endpoint panel

3. The Process Performance

The Tool is excellent run to run reproducibility for both etch rate and profile control. The process performance is summarized as follows:



Process details

Process gases CF$_4$, CHF$_3$, O$_2$, Ar

Process	Mode	Etch Rate (Å/min)	Selectivity	Uniformity (200mm wafer)
Polyimide	RIE	>1000	To SiNx >15:1	±6%
Depassivation (SiNx)	PE	>700		±7%
SiOx (BPSG;TEOS)	RIE	>350	To Poly-Si >7:1	±5%

Process features

Process provides excellent uniformity over 200mm wafers.

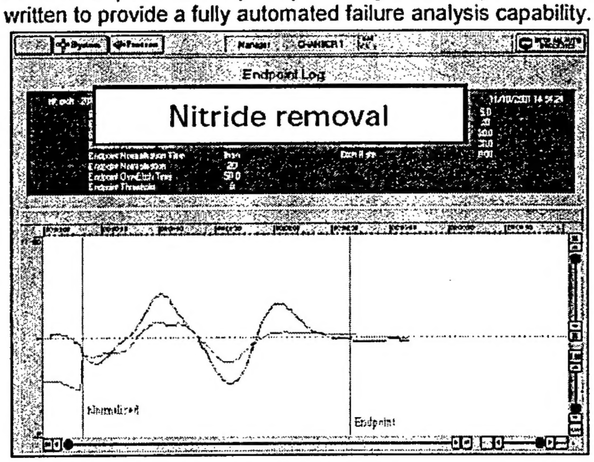
Clean removal of Polyimide, nitride and oxide is achieved.

Excellent run to run reproducibility for etch rate, uniformity, selectivity and profile control.

Process exhibits little dependence on electrode temperature, greatly simplifying hardware requirements and increasing process window.

Comments

Laser interferometry end-point detection can be used on layer removal steps. Multi-step recipes using laser endpoint can be written to provide a fully automated failure analysis capability.



4. The Technical Issues That Created the Need for the Tool

There are five on-going DOD projects that have and will be benefited from requested laser enhanced end point detection etch tool through this program. The projected research enhancement through this equipment grant is summarized in Table I. The thrust of the research affiliated with each program is also delineated. Dr. Chen serves as the principal investigators for all the programs. The DARPA program monitored by Bob Leheny is to build a board-level optical interconnection with a fully embedded VCSELs and detectors within the optical interconnection layer. The laser enhanced end detection based microstructure formation system can be used to provide the surface normal waveguide coupler. The other two AFOSR programs are aiming at

provide high speed waveguide modulation that can offer the direct modulation signal to feed the optically controlled PAA. The waveguide itself can be formed using the proposed fabrication system. The multifunctional material program supported by BMDO/ONR is to provide both modulation and amplification functions simultaneously in one integrated device module using polymeric material upon which the laser enhanced etching system can be used to form the needed microstructure. In the context of PAA application, the success of this program has provided and will continue to provide us with an easy way to build various true time delay module to test the accuracy and versatility of the beam steering capability of the phased array antenna system built by the core demonstration program. Finally the demonstration project is to employ wavelength multiplexing scheme for the fine tuning of the PAA scanning angle which will make the demonstration closer to a real phased array antenna (PAA) where continuous RF signal scanning is provided.

Note that all the research programs have strong involvement of undergraduate and graduate students. The Microelectronics Research Center at UT is one of the best-equipped research/education facilities in this country. A lot of hands-on training has already provided to students. The equipment requested through this program has further enhanced the research education facilitating hands-on experiences directly related to the formation of periodic microstructure targeted at the optical controlled phased array antenna application, which is of importance to provide system integration, when discrete optoelectronic components are made.

Large-angle laser beam scanners have important applications in many military fields, especially in the laser communications and target tracking systems of aircraft or space-craft. The device needs to be compact, stable, and thrifty in power consumption. The integrated laser beam scanner using our novel 2-D photonic crystal nanostructure satisfies all of these requirements. In addition, it offers a novel structure to realize the high-speed integrated 1×N optical switch essential to the node equipment of all-optical WDM networks. In contrast to current devices based on cascaded multi-stage 2×2 directional coupler switches, this new integrated 1×N optical switch will be a single-stage device with parallel processing capability, so that it is lower in loss and cross-talk, and more easily to be integrated with other devices. For these reasons, an impact on the commercial optical switch market is more than likely. Laser enhanced end detection based microstructure system can be used to form this fine periodic structure which is a cost-effective technique for large-scale fabrication of 2-D photonic crystals without random defects.

A novel slow-wave optical transmission line based on 2-D photonic crystals will find application wherever significant time-delay of optical signal is needed. We expect that nanosecond delay using only millimeters of waveguide can be realized by this new technology. The feature size of integrated optical TTD circuits can be reduced by two orders of magnitude, increasing the delay range that the integrated TTD devices can achieve. The technology will also help to investigate the physical issues of those optoelectronic devices which require long-time interaction between light and media.

Table I

The Projected Enhancement Generated from the 2000DURIP program for Five DOD On-going Projects

Project Name	Contract No.	Sponsor/ Program Monitor	Project Enhancement and Thrust of the Research
Manufacturable multi-dimensional high capacity optoelectronic interconnects	MDA 972-98 -1-0002	DARPA Bob Leheny	♦Formation of Polyimide based Waveguide Coupler
Electrooptic Polymer-based Coplanar Asymmetrical Unidirectional Multimode Waveguide Modulator for Multiwavelength Optical Interconnects	BMDO/ AFOSR F49620-97-1-0496	BMDO/AFOSR Charles Lee (AFOSR) Juergen Pohlmann (BMDO)	♦Formation of bottom layer waveguide unidirectional dumping wall which is a waveguide grating that can be formed using the Excimer laser system proposed herein.
Multi-functional Polymeric materials for Switching, Modulation and Amplification	N00014-98-C-0413	BMDO/ONR Dr. Y. S. Park	♦Formation of Waveguide Trench in an Rare Earth Ion Doped EO Channel Waveguide
Linear Electrooptic Polymer-Based EO Modulators	F49620-98-C-0015	AFOSR Charles Lee Juergen Pohlmann (BMDO)	♦Manufacturing of waveguide trench for polarization insensitive linear waveguide modulators ♦Demonstrate the low-cost advantages of polymer-based photonic components
Dispersion-enhanced Multimode Waveguide WDM for local area network	DASG60-98-C-0108	SMDC Stan Smith	♦V-grooves for Packaging enhanced WDM for local area network ♦Cost-effective approach for WDM devices

5. Achievements for DoD Projects through the System

(1) The Projects on multi-functional waveguide circuits sponsored by BMDO

The BMDO-sponsored polymer-based photonic devices have benefited from the equipment. The following results and demonstration were carried out at the Microelectronics Research Center at the University of Texas at Austin.

(A). Optical Waveguide Chips VOA Arrays

Variable Optical Attenuators (VOA)s are key components used to adjust the strengths of optical signals in modern optical communication systems, as shown in the attached Figure5 . When an optical signal is amplified using a fiber-optic amplifier, for example, the rate of amplification differs depending on the signal's wavelength. This makes reception difficult, since each channel has different signal strength. Solving this problem necessitated technology to eliminate the difference in signal strength, which led to the development of VOA devices. A VOA device located in the transmitting portion of a network makes for uniform optical output to the receiving portion by coordinating the optical input through adjusting for such characteristics of optical paths as the differences in amplification of each channel and transmission paths losses characteristic of certain wavelengths.

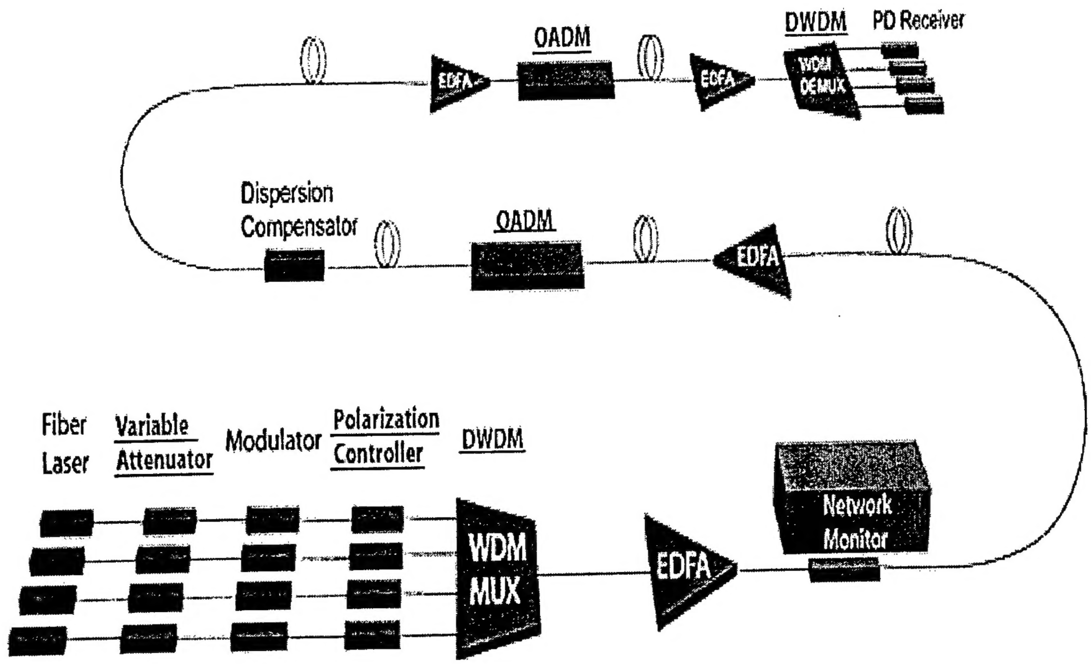
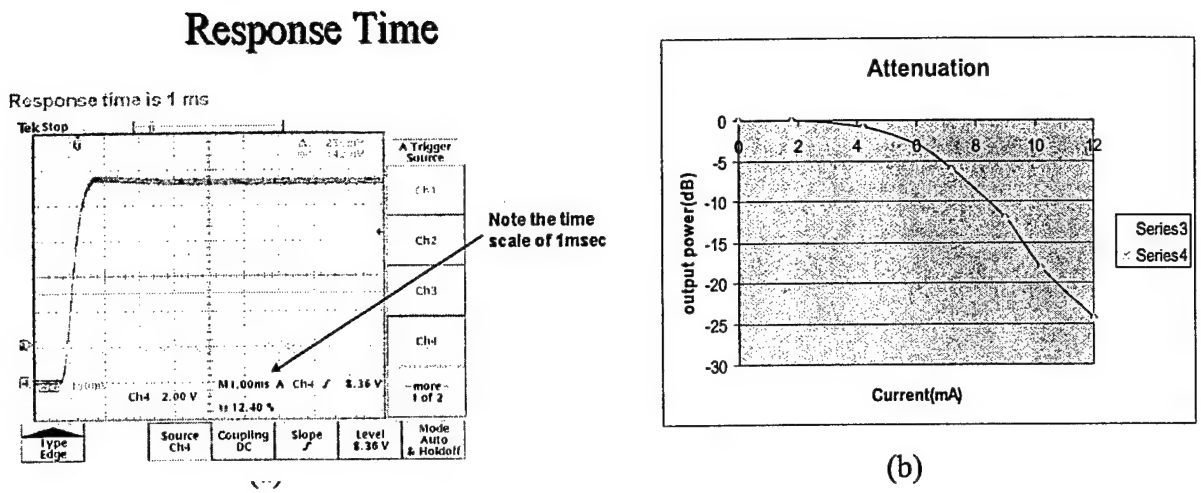


Figure5 . The Schematic of Optical Networks.

Optical Interconnects Research group led by Dr. Chen, At UT Austin, funded by BMDO developed cut-edge VOA array technology based on polymer waveguide. Here Polyimides Ultradel 9000 series are used in our experiments. The air trenches and waveguide arrayare etched by Laser enhanced end detection etching tool. The VOA is based on the thermo-optic effect of polymeric materials. The experiment results show the flatness of the insertion loss of the 16-consecuting channels is within 1dB, the dynamic range of VOA is larger than 25dB, and the response speed of VOA is in the order of ms. The characteristics of the VOA is shown in figure 6.



(b)

Figure 6. The characteristics of VOA, (a) response time ; (b) attenuation with applied current.

(B). Monolithic Module: modulator and amplifier

In order to realize a fully functional chip, it is expected that optical modulators, optical amplifiers, and even optical light sources and detectors can also be integrated into a optical waveguide chip. Here, we show our results to integrate optical amplifiers and optical modulators into the chip, which benefits for the new tool. The proposed structure of the monolithic module for modulator and amplifier is illustrated in Figure 7.

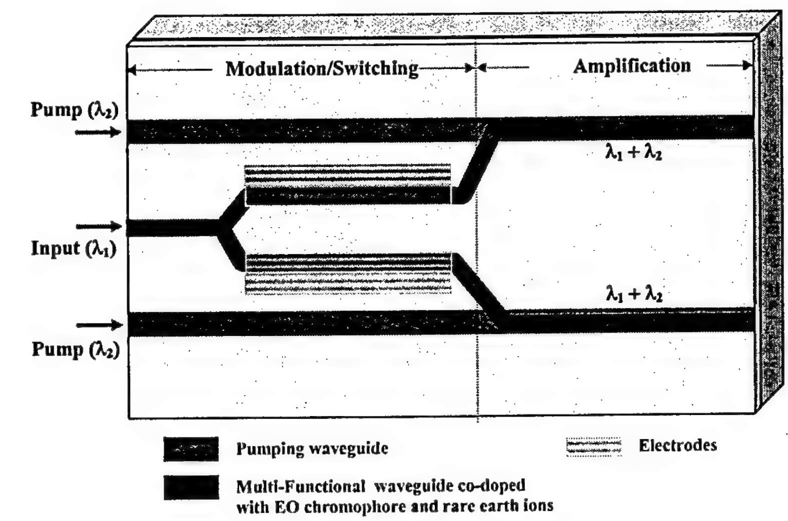


Figure 7. The schematic diagram of Monolithic Module: modulator and amplifier

The modulator is 1x2 Y-fed directional coupler modulator which is based on EO effect of polymer in waveguide circuits. If this modulator is used in an analog system, no bias is needed. The amplifier is a segment of waveguide circuit doped by rare-earth elements in which light signals and pump lights propagate together. We have

demonstrated both modulation and amplification of optical signals. Figure 8 shows the modulation result and Figure 9 give the amplification of the module.

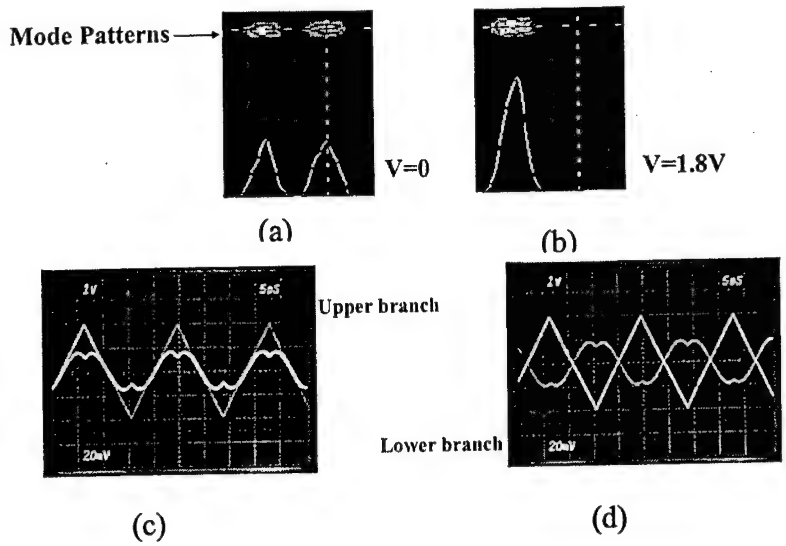


Figure 8. (a) & (b) Mode profiles coupled out of the two branches of the modulator under different driving voltages; Modulation curves displayed on an oscilloscope (c) the top branch; (d) the bottom branch.

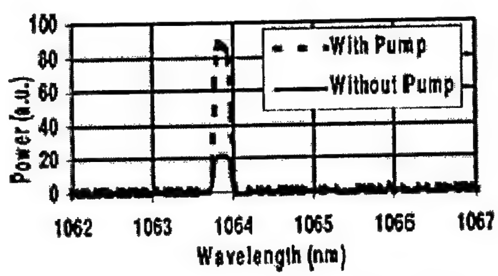


Figure 9. Demonstration of optical gain in the Nd-doped polyimide channelwaveguide sample. Gain is calculated by using the integrated power density values at the output before and after pumping the sample. Pump power5110 mW, signal power590 mW.

(C). Optical Waveguide Chips of True-Time-Delay Modules

In a phased-array radar system, using delay lines rather than phase shifters can eliminate the beam-squint phenomena. Therefore, true-time-delay (TTD) lines are important modules for wideband phased-array antennas. Recent years there has been a growing interest in applying the photonic technology to phased array systems, especially to optical beam forming and steering. The photonic technology gives better measures to form TTD networks than the traditional electronic technology.

Figure 10 shows a schematic diagram of an optical TTD network using switched optical waveguide circuits. In this configuration, optical waveguides with various lengths are designed as the delay lines and 2x2 optical switches are used to control the light route.

Thus the optical RF signal is optionally routed through waveguide delay lines whose lengths increase successively by a power of 2. Since each switch allows the signal to either connect or bypass a delay line, a delay T may be inserted which can take any value, in increments of $\Delta\tau$, up to the maximum value $T_{max}=(2^N-1)$ $(\Delta\tau)$ if N waveguide delay lines are designed. Using polyimides, this TTD network can be monolithically integrated on an optical waveguide chip. As a result, it eliminates the most difficult optical packaging problem associated with the delicate interfaces between optical PM fibers and 2x2 switches. Meanwhile, such a monolithic approach offers more precision for the RF phase than the fiber-delay-lines because the waveguide length is photolithography-defined with an accuracy of sub-micrometer.

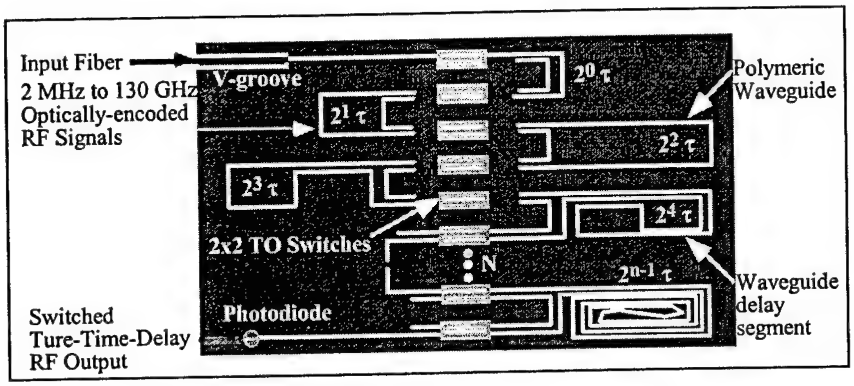


Figure. 10 A multifunctional optical waveguide chip for photonic phased-array antennas: a programmable optical TTD module using monolithically integrated polymer-based waveguides and 2x2 switches.

To design and fabricate this chip, how to structure the long delay-line waveguides is one of the key issues. Figure 11 shows a ten-meter long polyimide waveguide circuit fabricated by using the tool.

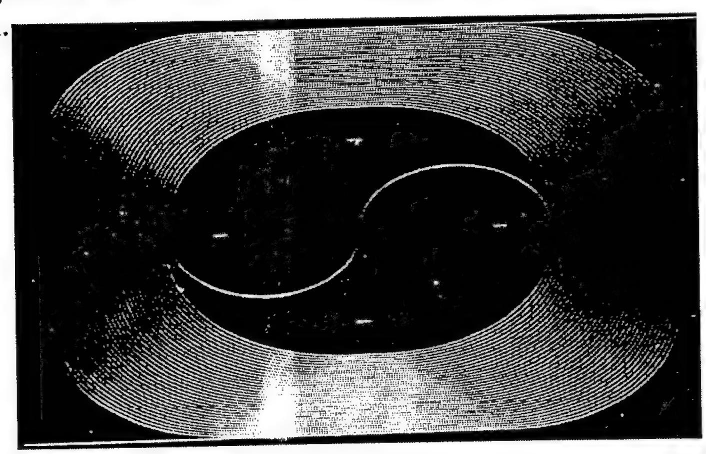
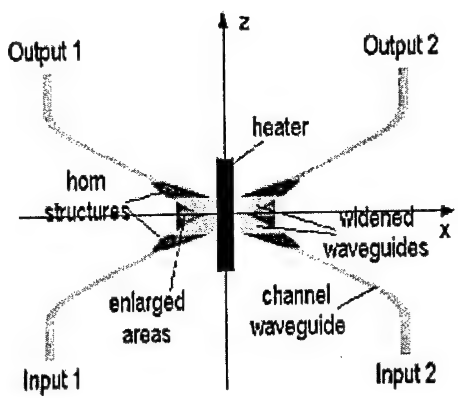
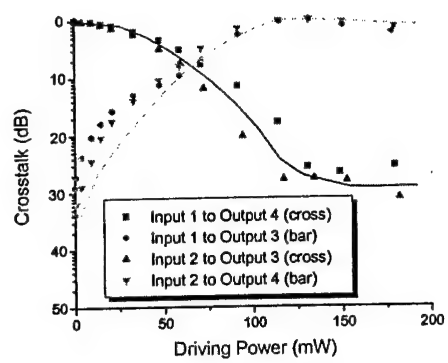


Figure.11 A ten-meter long polymeric waveguide delay line

Another key issue is the design of the optical switch. Because the TO effect of polymeric materials is polarization-independent and sufficiently strong, TO polymeric switches are the potential candidates for the integrated optical TTD module. We designed a 2x2 total-internal-reflection (TIR) polymeric switch with a X-junction, as shown in Figure 12(a), for this integrated module. Using the same processing techniques as the waveguide delay lines, this TO optical switch was fabricated. Figure 12(b) gives the characteristics of the 2x2 polymeric switch. The crosstalk measured is less than –28dB. The switching power is about 132mW, which can be lowered to 50mW by improving the driving efficiency. Figures 12(c) shows the light signal passing through the channel and (d) shows the signal switching.



(a)



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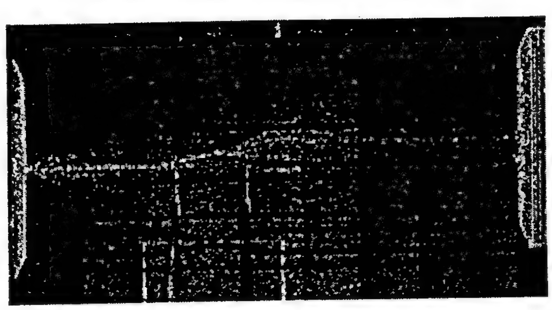
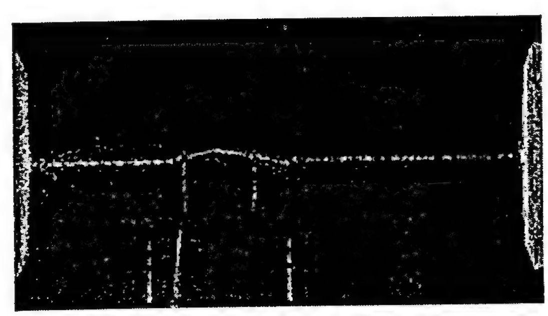


(c)



(d)

Figure.12 2X2 polymer optical switch, (a) The structure of the 2x2 TO TIR polymeric switch; (b) The analytical and measured switching characteristics; (c)light signal passing through the channel and (d) the signal switching.

(D). True Time Delay Module for a K-band Phased Array Antenna System Demonstration

The BMDO-sponsored photonic phased-array antenna system program monitored by Dr. Charles Lee fully benefited from the system. The system was demonstrated in this program at UT Austin.

A 1-to-64 (6-bit(2^6)) optical true-time delay module is designed, fabricated and packaged for squint-free beam steering in phased array antennas, providing linear time delays ranging from 0 to 443.03 picoseconds. The phases versus RF frequencies are measured to verify that the time delay is independent of RF frequencies. The optical true-time delay module is integrated into a K-band (18 GHz – 26.5 GHz) phased-array antenna system. Far field patterns at different frequencies over the entire K-band are measured and compared with simulated results to verify the system's wide instantaneous RF bandwidth. The Q factor is measured to be 10.20 of the true-time delay optical link transmitting 2.5Gbit/s random digital signal.

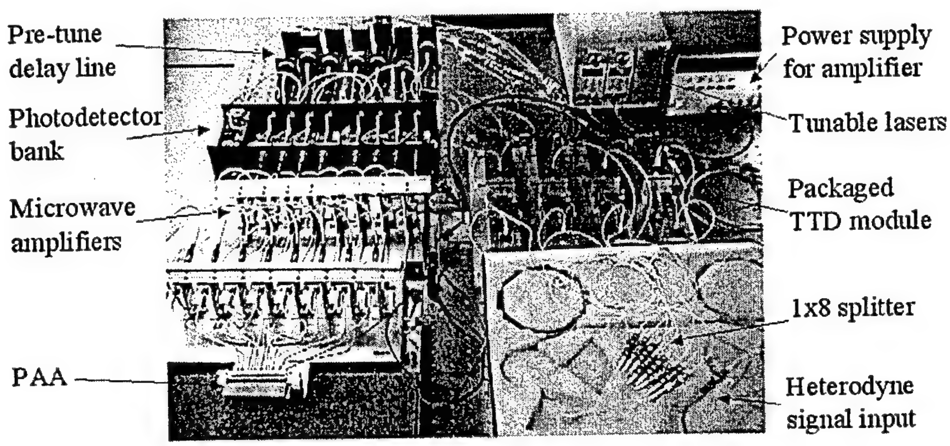


Figure 13. The integrated K-band PAA system.

The integrated K-band PAA system is demonstrated in Figure 13. A microwave signal is generated by the heterodyne technique using two external cavity tunable semiconductor lasers. The optical carriers are distributed into the eight sub-units of the TTD module by a 1-to-8 splitter. After desired time delay, the microwave signals with correct phase relationship are detected by photodetectors and fed into eight antenna elements individually after amplification. The on/off states of photodetectors are determined by a computer controlled printed circuit board, so that the TTD module can be used in both of single angle scanning and full beamformer application, with the beam steering speed of the PAA determined by the computer speed and program running time (~ microsecond).

Far field patterns of the PAA are measured to verify the instant broad RF band. Far field patterns at 18.5^0 scanning angle corresponding to 18 GHz, 22 GHz and 26.5 GHz are shown in Figures 14. From Figure 14, it can be seen that the simulation results and

measured data agree very well. Furthermore, the PAA scanning angle is independent of the RF frequencies over the entire K-band, and this further prove the property of time delay being independent of RF frequencies.

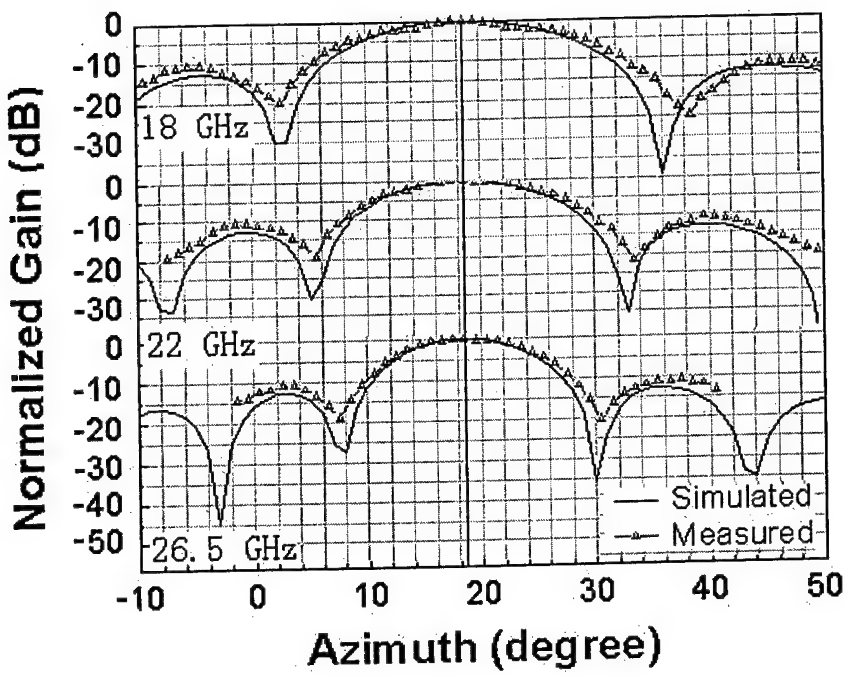


Figure 14. The Far field patterns at scanning for different frquencies.

In practice, information is transmitted in an encoded digital signal format. Therefore, a 2.5 Gbit/s random digital signal from Agilent 8133A pulse generator is employed to evaluate the degradation of the TTD link. In order to exclude the effect of RF mixer and transimmsion, a 2.5 Gbit/s digital signal is directly modulated onto the optical carrier. HP 83480A Digital Communications Analyzer is used to measure the Q factor and jitter in effective time, with the trigger coming from the pulse generator. Q factor is a measurement of signal noise ratio and equal to $(S_1\text{-}S_0)/(N_{1,rms}+N_{0,rms})$, and the signal is approximately Gaussian distribution. The back-to-back Q factor of the 2.5 Gbit/s random digital signal is measured to be 50.42, while a Q factor of 10.20 and jitter of 12.3 ps is obtained after insertion of the TTD link with the eye diagram shown in Figure 15. The main reasons for the degradation of Q factor and jitter are the noise coming from modulators, lasers, photodetectors and amplifiers. The Q factor does not change with scan angle due to the passive nature of the TTD module.

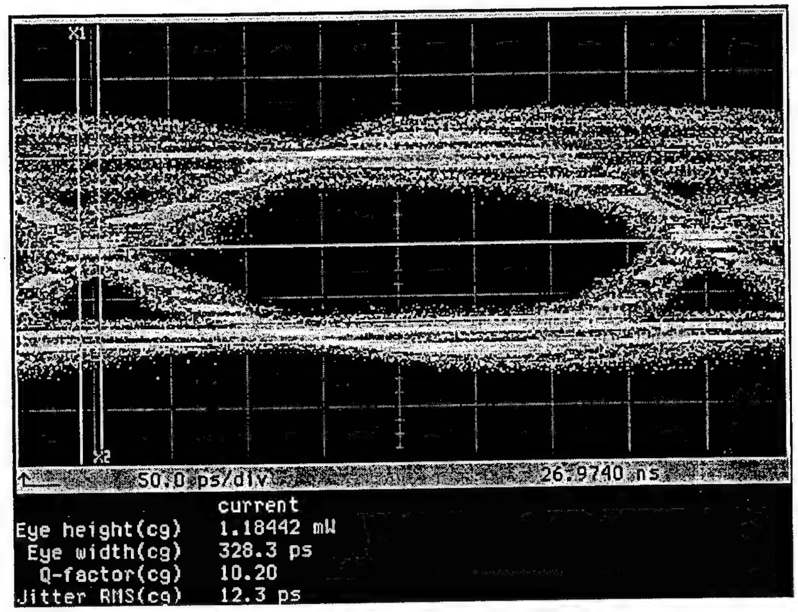


Figure 15 The Eye diagram of TTD link

(2). The DoD-sponsored polymer-based photonic devices

(A) Fully embedded PCB level optical interconnects

Recently, the ability of high speed data transfer rate in high performance computer systems is very important with the high speed CPU which operates giga-hertz region. Data transfer between device chips or boards is the major bottleneck in electrical transmission lines; especially the length of copper line is greater than characteristic resistance. Electrical transmission lines inherently affected by interferences such as cross talk and skew and reflection. Several optical interconnect approaches were introduced to resolve limitations. However, many of demonstrated systems in board level optical interconnection caused the packaging difficulty because they were using hybrid integration approaches for electronic and optoelectronic components which were placed on the same surface of board. We employed a fully embedded PCB (Printed Circuit Board) level optical interconnects, which is sponsored by DAPA from DoD, to solve transfer bottleneck, packaging and robustness. It provides not only process compatibility with a standard PCB process but also reduced footprint of PWB due to all optical components such as light sources, planar waveguides and detectors are buried between electrical layers. The structure of optical interconnects is shown in Figure 16.

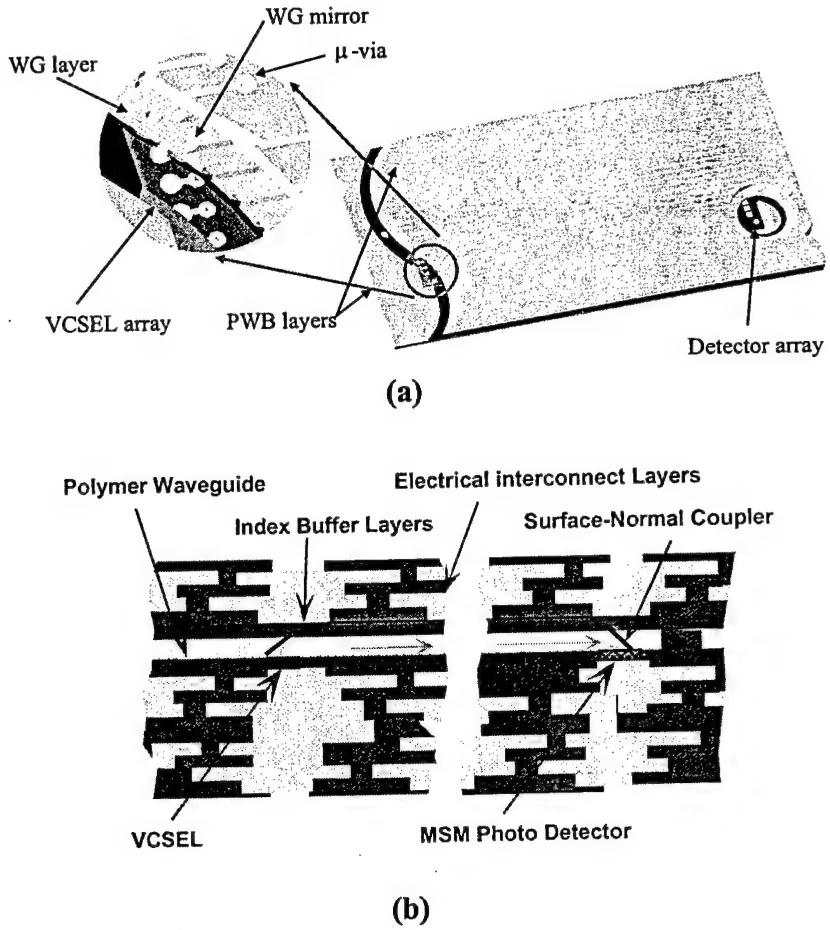


Figure 15. Diagram of Fully Embedded PCB Level Optical Interconnects (a) and its layer structure (b).

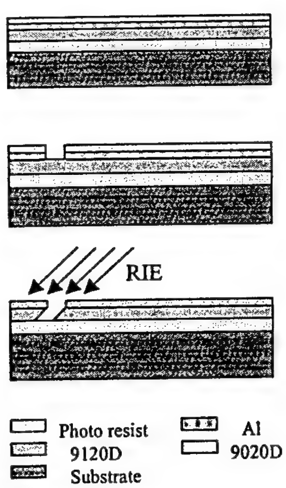
All optical components including VCSEL array, photo-detector array and planarized waveguide are embedded between electrical layers in a fully embedded board level optical interconnects. All the optical devices need fabricate with fine etching system and they are all benefit from the system.

Link waveguide with 45 degree mirror

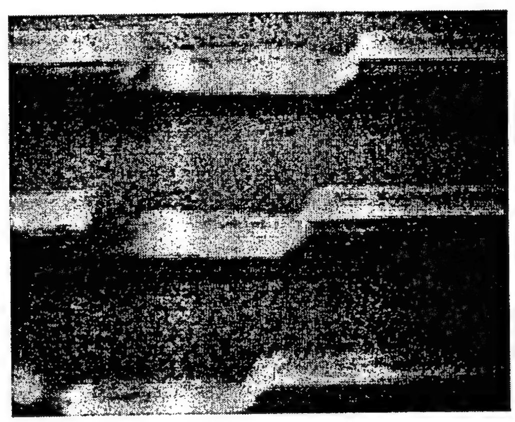
Polyimides are the materials of choice for the waveguide fabrication in the optical interconnects layer. Specifically, Ultradel 9120D and 9020D (Amoco Chemicals) show promising features for optical component fabrication. The polyimides 9120D and 9020D having refractive index at the wavelength of 850nm of approximately 1.56, and 1.54, respectively, (which can be tailored slightly by controlling the processing conditions) form waveguides with excellent propagation properties and light confinement. The propagation loss of the TE_0 mode in such polymer channel waveguide was measured to be 0.21dB/cm at 850nm and 0.58dB/cm at 632.8nm.

Figure 16 (a) shows the main processing steps for fabricating the polymer channel waveguide array and the 45-degree TIR micro-mirror couplers. To form the two-layer structured channel waveguides, we first spin-coat the substrate with a 6~7 μm-thick layer

of 9020D, and perform a short soft-bake to remove the residual solvents. This layer acts as the buffer layer or bottom cladding. A similar process is carried out to forms a core layer of 6~7μm-thick 9120D on the bottom cladding. Both layers are patterned through photolithography forming an array of channel waveguides with 50μm width and 12~13μm height. The length of the waveguide can be varied to satisfy the requirements of specific applications. The formed waveguide array has 250μm center-to-center separation between adjacent channels. 45-degree TIR micro-mirror couplers are formed within the channel waveguide by laser enhanced end detection reactive ion etching (RIE) technique. A layer of 0.3μm-thick aluminum deposited on the surface serves as the protective mask in the RIE process. Using photolithography and wet etching, a 50μm ×50μm square window is opened in the aluminum layer at the end of each channel, where the micro-mirror is to be etched. During the RIE process, the sample is placed at a 45-degree angle with respect to the electrode in the chamber. A Faraday cage covers the sample so that the directional high-speed ions attack the polymer at a 45-degree angle with respect to the substrate through the square openings. This process results in a 45-degree slanted etched surface formed on each channel waveguide, which can provide input or output surface-normal coupling of light into or out of a channel waveguide. Figure 16 (b) gives the photo of link waveguide with 45-degree mirror.



(a)



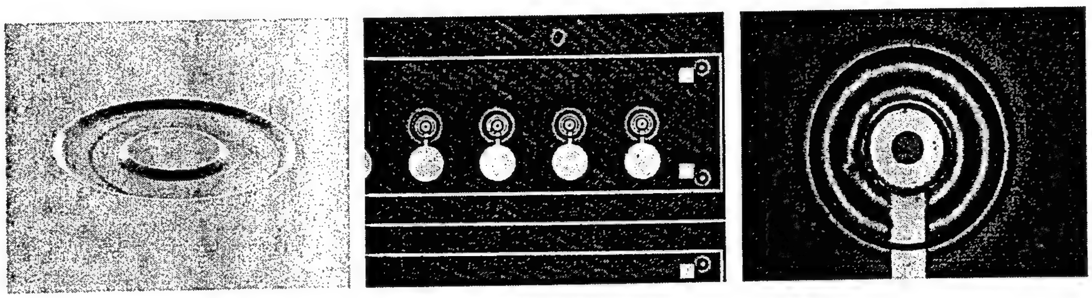
(b)

Figure 16. (a) Procedures to fabricate polymer channel waveguide with fully-embedded 45-degree TIR micro-mirror coupler; (b) SEM micro photograph of polymer channel waveguide array with fully-embedded 45-degree TIR micro-mirror coupler

Fabrication VCSEL and measurement of thermal resistance

The VCSEL's epi structure was grown on GaAs substrate. An etch stop layer of 100nm thick was grown and then GaAs buffer layer, 40.5 pairs of n-DBR, three GaAs quantum wells, and 23 pairs of p-DBR were grown. Total thickness of epi structure is 10μm.

Fabrication started with wet etching and laser enhanced detection RIE etching to make annular shape trench which provides isolation of each device and defines oxide confinement region. The wet oxidation was carried out in quartz tube furnace which was held at 460°C. Spin on glass (SOG) was coated on the entire wafer for electrical isolation and side wall sealing. The SOG opening process was followed for p-contact metallization. After finishing device processes, thinning process was followed. Devices were mechanically thinned down to 250μm. These devices were back etched using wet etchant to make various thick ,VCSELs(200, 150,100μm). Ten micrometer thick VCSEL was prepared by substrate removal technique. Figure 17 shows the SEM photo of VCSELs fabricated.

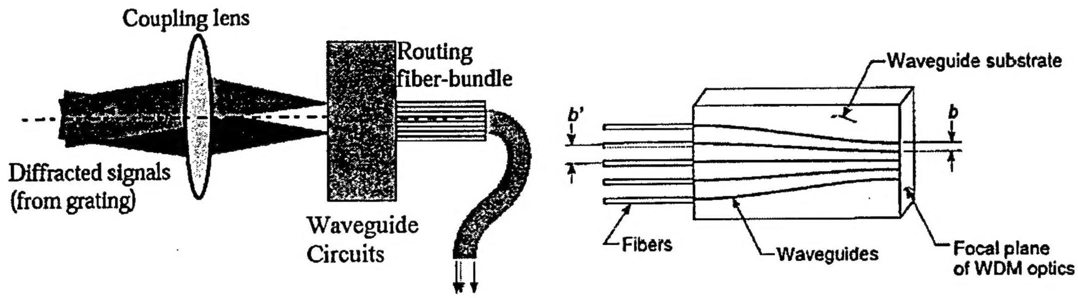


(a) (b) (c)

Figure 17. Photographs of fabricated VCSEL array, (a) SEM picture of annular shape trench; (b)Pictures of linear VCSEL array and (c) Enlarged view of VCSEL.

(B) WDM for optical interconnects & networks

For high bit rate long haul optical communications, high count dense wavelength division multiplexers (DWDM) with channel spacing smaller than 100GHz (wavelength spacing smaller than 0.8nm) are the key components. The requirement of the DWDM devices includes: low insertion loss, insensitive to temperature, low polarization dependent loss, high bit rate, large 1dB pass band, small device size, etc. Our DWDM has free space grating based structure, which is designed insensitive to temperature and can have as many channels as possible to cover the whole C-band or L-band with channel spacing of 50GHz or 100GHz. The challenging issues come with the bit rate, 1dB pass band and the device dimensions. Intense study shows that the maximum signal bit rate is limited by the pulse broadening effect introduced by the diffraction element. To solve this problem, the output channel pitch should be as small as possible. In the mean time, by decreasing this channel pitch, the 1dB pass band can be increased and the device dimensions can be shrunk. A polymer waveguide chip is inserted into the WDM unit to act as a concentrator with channel pitch less than 18μm. The waveguide concentrator was fabricated by using the laser enhanced end detection etching system. Figure 18 (a) shows the structure of WDM adding a waveguide concentrator



(a) (b)

Fig. 18 (a) Schematic illustration of a hybrid MUX based-on free-space optics and diffraction gratings. (b) A waveguide concentrator between the fiber bundle and the free-space focal plane.

Figure 18 (b) shows the structure of the waveguide concentrator we designed. The ratio of the waveguide spacing b to the mode size of the waveguide at the concentrated end for the focal plane of WDM optics is designed to meet the requirements of the channel passband. At the other end of the waveguide concentrator, the waveguide spacing b' and size are designed to match the fiber-array V-groove and the optical fibers, respectively. To decrease the crosstalk caused by the reduced spacing of the adjacent waveguides at the concentrated end, air trenches are set between waveguides, as shown in Figure 19. The analytical results show the crosstalk can be lowered down to below –35dB.

The air trenches are set in the middle of every two adjacent waveguides. They made the horizontal mode size narrower at the concentrated end while at the fiber-coupling end they have little influence on the field distribution of the waveguide mode. Because the whole chip is long enough, the mode-transforming loss from one end to the other end and the related waveguide bending loss can all be ignored.

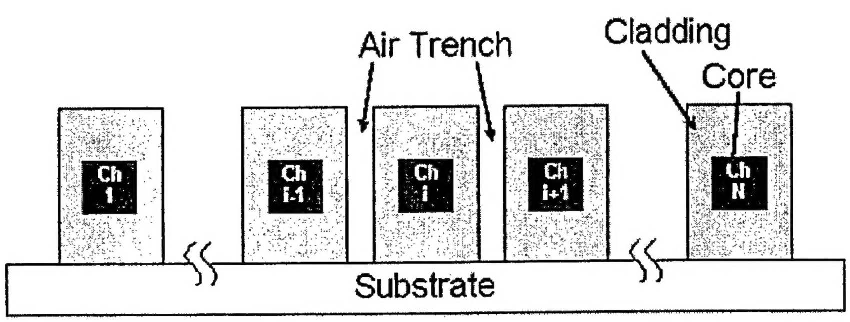


Fig. 19 The Cross-section of the waveguide concentrator at the end for the focal plane of WDM optics

Just because the polymeric waveguide concentrator is employed in the design of grating-based WDM multiplexers/demultiplexers, polymeric VOA can be very easily integrated

into the whole WDM components by monolithically designing and fabricating the VOA with the waveguide concentrator in an optical waveguide chip.

Optical interconnects group led by Dr. Chen, at UT Austin, and sponsored by *DoD Funding agencies, such as, BMDO, Army SSDC, DARPA, Office of Naval Research, AFSOR,* has developed the unique technology, that is, free space optics with guide optics, to develop WDM devices, which can be both single mode and multimode for optical interconnects & networks. By using the technology we have demonstrated a series of WDM devices including single mode, multimode, coarse, dense and multideck structure WDM devices. The all the WDM devices are reliable, athermalized and cost-effective with high performance have the applications in optical networks and laser free space communications. The followings are the spectrum of the transmissions of the devices.

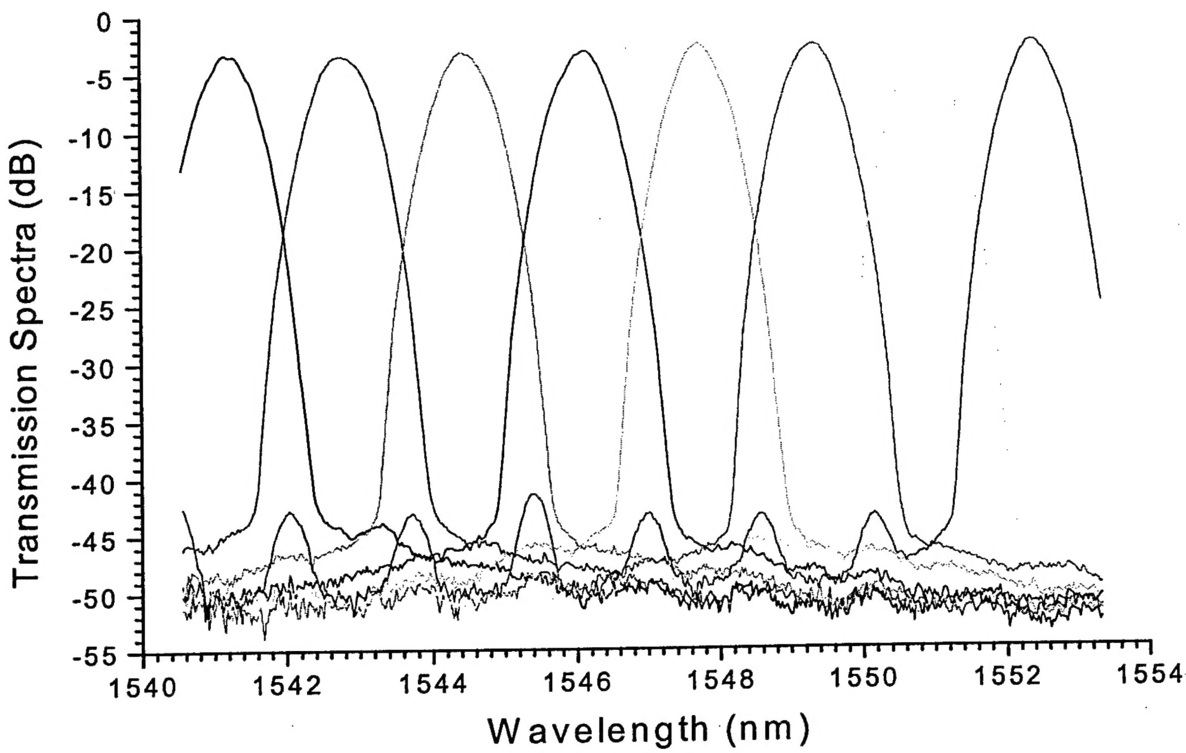


Figure 20. The Transmission spectra of 200 GHz multimode WDM Device

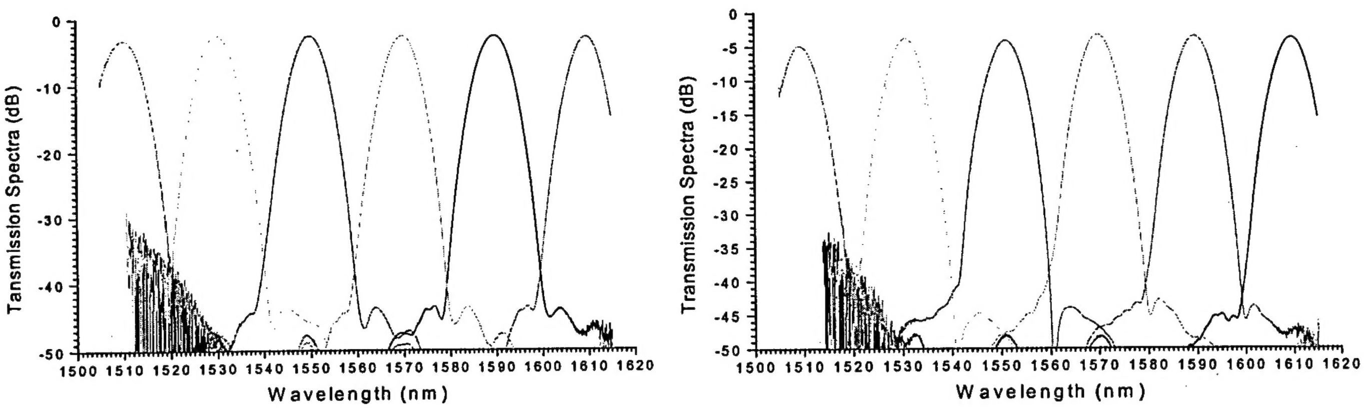


Figure 21. The transmission spectra of double-duck 6-Channel CWDM device, the left for one layer and the right for another

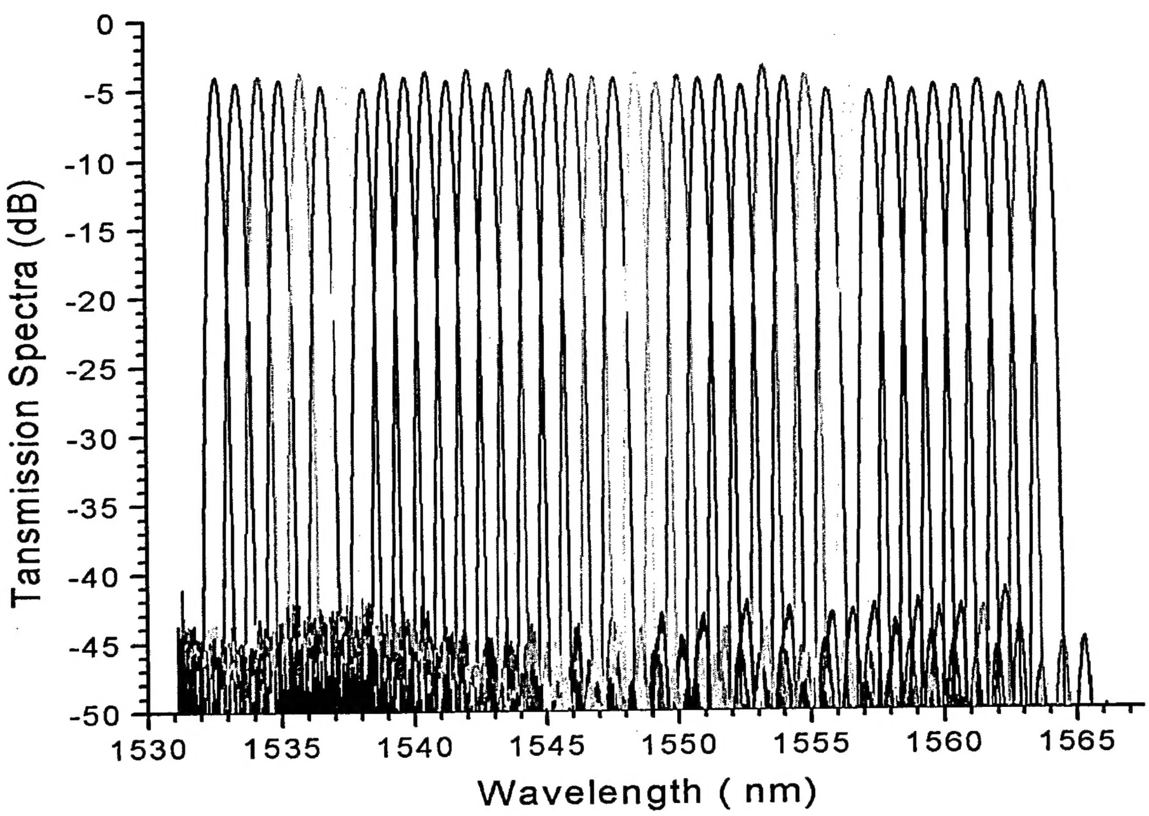


Figure 22. The Transmission spectra of 40 Channel 00 GHz WDM Device